Piezoelectric characterization of Si-photonic integrated PZT thin film

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Lead Zirconate Titanate (PZT) with its high piezo-electricity and electromechanical coupling coefficient (in bulk) promises to be an efficient transducer for electro-optomechanical applications. In this work, we investigate the piezoelectric response of a thin film of Si-photonic integrated PZT by exciting surface acoustic waves (SAWs) with an interdigitated transducer (IDT). Furthermore, we demonstrate the optical phase modulation from the SAW on a PZT integrated waveguide circuit.

Introduction

Silicon photonics offers a fast-growing technology platform with applications in several important areas such as telecommunication[1], medicine[2], quantum information processing[3] etc. A photonic integrated circuit (PIC) consists of several components like sources, splitters, filters, modulators, detectors etc. Hybrid integration of novel materials is essential to realize these components on Si-photonics chip. In this study, we explore the piezoelectric properties of a Si-photonic integrated thin film of Lead Zirconate Titanate (PZT).

PZT is a ferroelectric material with a very high piezoelectric coefficient and electromechanical coupling coefficient in bulk. However, in most cases PZT deposition involves a Pt-buffer layer for preferential crystal orientation and to avoid lead diffusion, which makes it optically lossy. Recently a novel approach for depositing highly textured PZT-films, using a thin transparent lanthanide based buffer layer, was developed. The high quality of the resulting film was proven through the demonstration of efficient electro-optic (EO) modulators on a SiN photonic platform (effective EO coefficient of ±70 pm/V) and low optical loss (1dB/cm)[4]. Given the promising electro-optic results which proved the quality of the material, we now explored the piezoelectric response of these thin films here by exciting surface acoustic waves (SAWs).

SAW excitation with an interdigitated transducer (IDT)

A SAW is usually excited by applying an RF signal to an IDT. An IDT consists of alternate electrodes facilitating alternate electric fields (as shown in figure 1.a) which creates periodic strain in the piezoelectric material beneath the IDT. When the RF frequency applied to the IDT matches with SAW resonance frequency, a SAW is launched in both directions. The wavelength of the primary SAW mode is equal to the period of the IDT.

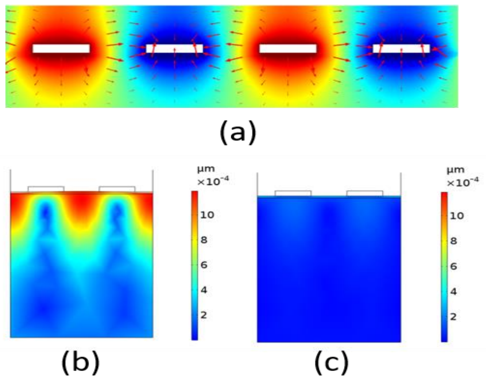

Figure 1 (a) Simulation of the Electric field distribution of IDT/PZT/Si device (cross-section) shows the alternating field polarity. (b) simulation of the electrically driven total displacement for an in-plane poled PZT layer (c-orientation). (c) simulated total displacement for an out-of-plane poled PZT layer (a-orientation). For the electro-mechanical simulation, an IDT of period 8 µm is excited with a 10 V AC signal of frequency equal to the mechanical eigen-frequency of the structure (SAW frequency).

In *Figure 1*(a) we show the Comsol simulation of the electric field due to an applied AC signal on the IDT deposited on 200 nm of PZT on Si. In figure 1(b) and 1(c) we show the Comsol simulated mechanical displacement on applying an AC signal to the same device in different poling configuration. These simulation results prove that in order to have an effective excitation of SAW, PZT should be poled in the direction of the applied electric field (in-plane). To achieve that, we first fabricated a parallel rectangular electrodes on a PZT/Si sample by direct write lithography (DWL) and Ti/Au 20nm/350nm deposition. After poling the sample using these electrodes, next we fabricated the stand-alone IDT in the poled region. We characterized the SAW excitation by measuring the electrical reflection parameter S_{11} with a vector network analyzer (VNA) as shown in Figure 2.

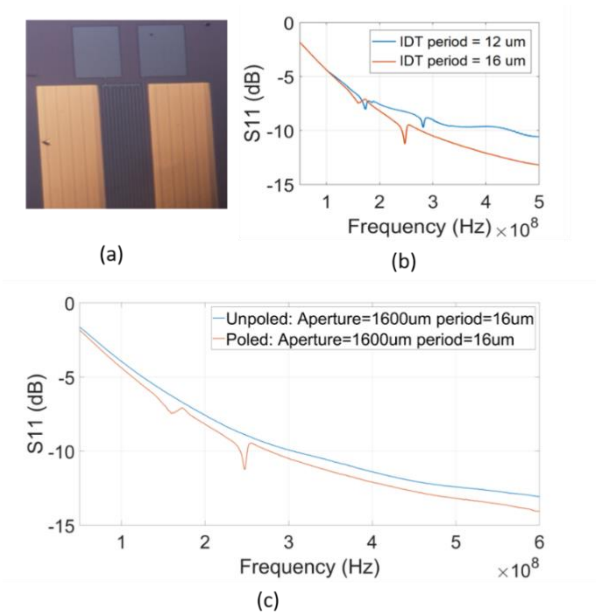

Figure 2 (a) Microscope image of IDT with period 12 µm (grey color), 6 periods are fabricated in between the poling electrodes (yellow color) with spacing of 80 µm. The poling voltage= 820V is applied for 40 minutes. (b)The electrical S_{11} parameter shows a dip (corresponding to SAW excitation frequency) varying consistently with the IDT period. (c) The electrical S_{11} response shows SAW excitation for the poled PZT, while unpoled PZT shows no such response, thus corroborating the conclusion from the simulation results.

The biggest drawback of poling with the rectangular electrodes is that the IDT structure (e.g. period, number of periods etc.) has to be limited in order to fit in a given (limited) poling region. This limit makes this poling method impractical for integrated devices. Hence, we tested poling the PZT using the IDT itself. Now, due to the alternate poling direction in the neighboring electrodes, the SAW resonance frequency is supposed to double which we indeed observed in Figure 3(b), confirming the excitation of SAW.

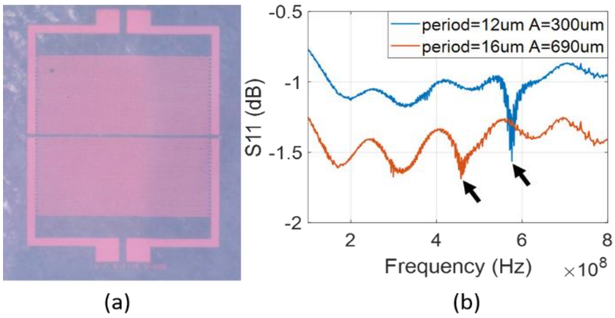

Figure 3 (a) Microscope image of an IDT-IDT system. We apply a poling voltage on the IDT for 30-40 min. (b) S_{11} shows that now for the IDT with period 12 µm, the SAW frequency has almost doubled (310MHz to 590 MHz). Further, the resonance frequency varies consistently with the change in IDT period. The ripples in the S_{11} signal are due to the reflections in the RF cable.

PZT thin-film integration with photonic system

Following the successful demonstration of SAW from a stand-alone IDTs on PZT/Si sample, we integrated similar IDTs with silicon waveguide circuits. The waveguides were defined in an SOI wafer with a 220 nm thick top silicon layer on a 2 µm buried oxide layer. Following waveguide definition, the devices were planarized using oxide deposition and chemical mechanical polishing (CMP). Next, similar as described above we deposited a 20 nm thick lanthanide-based buffer layer and a 200 nm thick PZT-layer. We then defined IDTs on top of the PZT layer as shown in Figure 4(a).

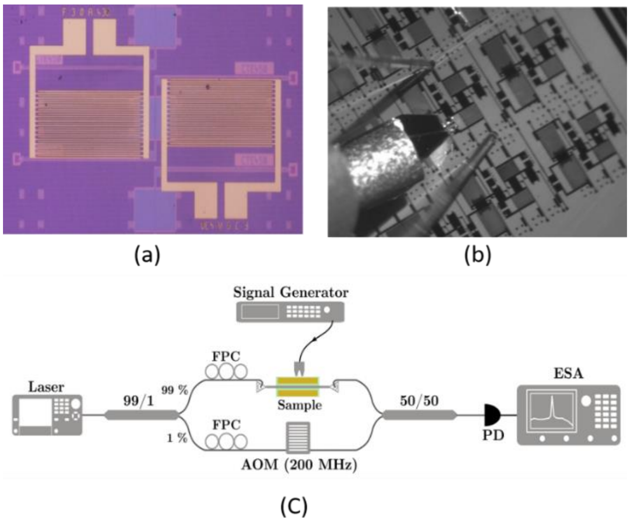

Figure 4 (a) A microscopic image of a silicon TE waveguide (width 550nm) integrated with an IDT (period 12 µm, 20 periods, aperture size 180 um). (b) camera view shows the landing of a GS probe (100µm pitch) on IDT electrode pads. Two optical fibers are aligned with the grating couplers for the optical transmission measurement. (c) A heterodyne-setup is used for the measurement of the phase modulation in a single waveguide.

To characterize the phase modulation in the waveguide from the SAW, we built a heterodyne setup as shown in figure 4(c). We mix the optical signal from the DUT with that coming through the acousto-optic modulator (AOM) with a modulated frequency at 200 MHz, in a fast photodetector (PD) and connect them to an electrical spectrum analyzer (ESA). This mixing results into two sidebands at frequencies $\Omega_{SAW} + \omega_{AOM}$ and $|\Omega_{SAW} - \omega_{AOM}|$ which we observe in our preliminary results from the ESA data as shown in figure 5(a).

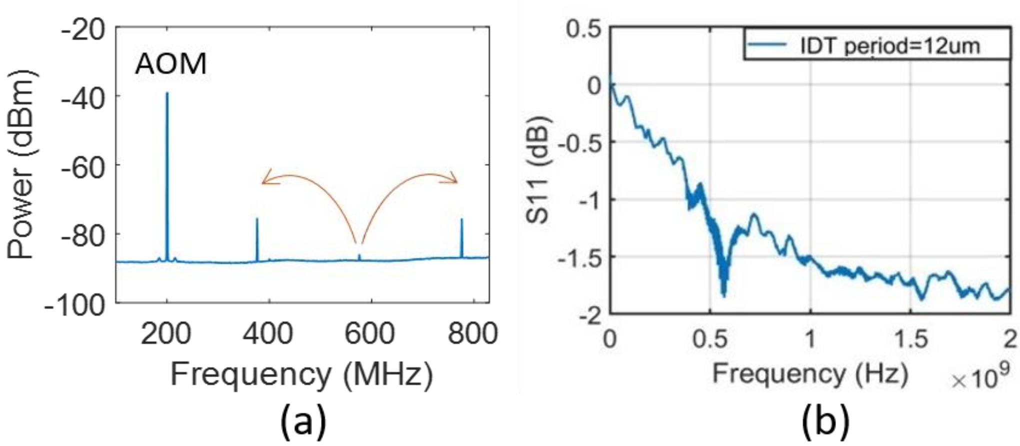

Figure 5 (a) Two sidebands appear from the mixing. The maximum sideband amplitude (phase modulation) occurs at RF frequency of 576 MHz. (b) The S11 parameter from the same IDT shows dip at 576 MHz. These results prove the excitation of SAW on the PZT and the first order mode frequency of SAW is 576 MHz for the given IDT structure of period 12 µm.

The phase modulation from the SAW is given by $\phi = \beta * \sin(\Omega_{SAW} * t)$; where β is the phase change amplitude and Ω_{SAW} is the SAW excitation frequency. β is calculated from the peak ratio of the AOM and sidebands in the ESA spectrum. From the data shown in Figure 5(a), β is calculated to be 0.03 radians. This phase change amplitude (β) corresponds to a $V_{\pi}L \approx 3.35$ V cm. For a similar PZT layer, earlier the electro-optic modulator has been reported to give $V_{\pi}L \approx 3.2$ V cm[4]. Hence, we notice that even without any optimization, our first preliminary results already give a competitive figure of merit.

Conclusion

We have shown through simulation and experiment that for an efficient SAW transduction, it is essential to have an appropriate poling of the PZT domains. With a suitable poling, we have demonstrated the very first piezoelectric response of our photonic integrated PZT layer by exciting a SAW, which is confirmed with both electrical S_{11} measurement and optical phase modulation in a waveguide. The preliminary phase modulation data, without any device optimization, already shows promising electro-optomechanical response. Thus it opens the possibility of combining the piezoelectric effect of PZT with photonic components to realize various photonic applications such as filters, on-chip acousto-optic modulations etc.

Acknowledgment

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